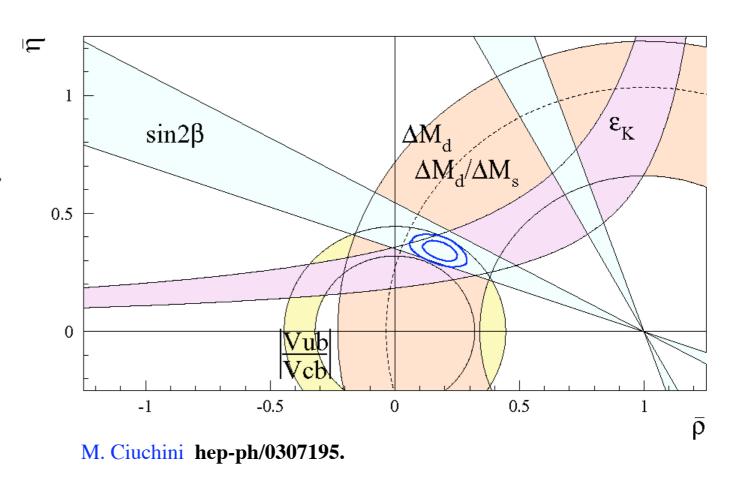
Lattice Gauge Theory at Fermilab

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Additional material at: http://lqcd.fnal.gov.

DoE Annual Review Fermilab March 24, 2004 Lattice QCD calculations have become essential to some of the central goals of the HEP experimental program.



E. g., potential to improve the ρ - η plane is huge. Of the five best constraints:

K K bar mixing currently dominated by lattice uncertainties.

B B bar currently dominated by lattice uncertainties.

Bs Bs bar will be dominated by lattice uncertainties.

Vub: $(B \rightarrow \pi l \nu)$ will be dominated by lattice uncertainties.

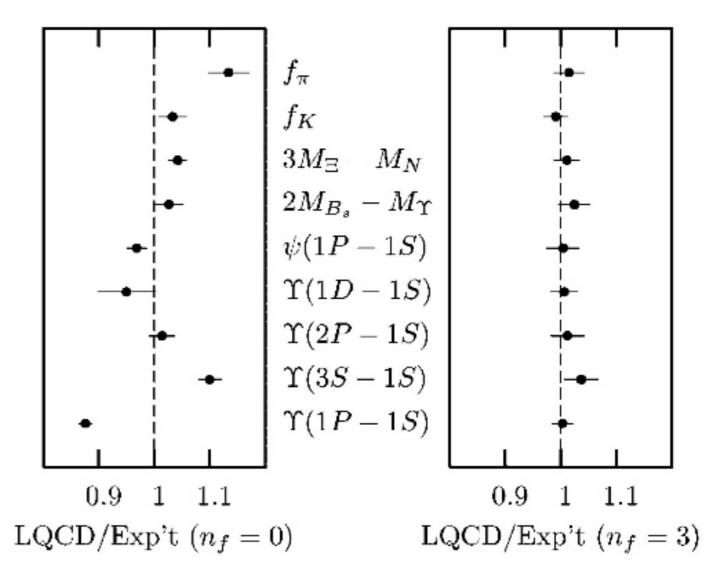
sin₂β: dominated by experimental uncertainty.



Recent big progress with unquenched improved staggered fermions.

Several groups
compared their <u>simplest</u>
calculations. 10%
disagreement quenched

→ few per cent
agreement unquenched.



C.T.H. Davies et al.,

Phys.Rev.Lett.92:022001,2004, hep-lat/0304004.

What about slightly more complicated quantities? Do other light quark methods agree?



The progress was written up in nice articles in Physics Today and Nature.

news and views

High-Precision Lattice QCD Confronts Experiment

C. T. H. Davies, ¹ E. Follana, ¹ A. Gray, ¹ G. P. Lepage, ² Q. Mason, ² M. Nobes, J. Shigemitsu, H. D. Trottier, and M. Wingate 4 (HPOCD and UKOCD Collaborations)

C. Aubin ⁵ C. Bernard ⁵ T. Burch ⁶ C. DeTar ⁷ U. M. Heller, J. E. Hetrick, J. Osborn, I

M. Di Pierro, 12 A. El-Khadra, 13 A. S. Kronfeld, 14 P. B. M. (HPOCD and Fermilab Lattice

¹Department of Physics and Astronomy, University o ²Laboratory for Elementary-Particle Physics, Cornell ³Physics Department, Simon Fraser University, Va. ⁴Physics Department, The Ohio State Univer ⁵Department of Physics, Washington Universi Department of Physics, University of Arizo ⁷Physics Department, University of Utah, ⁸Department of Physics, Indiana University, ⁹American Physical Society, One Research Road, Boa ¹⁰University of the Pacific, Stockton ¹¹Department of Physics, University of California, ¹²School of Computer Science, Telecommunications and Information ¹³Physics Department, University of Illinois, ¹⁴ Fermi National Accelerator Laboratory.

> We argue that high-precision lattice QCD is now possi improved staggered quark discretization. We compare a wi in QCD with experiment, and find agreement to within stat We also present a new determination of $\alpha_{\overline{MS}}^{(5)}(M_Z)$; we obt of this breakthrough for phenomenology and, in particular

PACS numbers: 11 15 Ha 12 38 Aw 12 38 Gc

For almost thirty years precise numerical studies of nonperturbative QCD, formulated on a space-time lattice, have been stymied by our inability to include the effects of realistic quark vacuum polarization. In this paper we present detailed evidence of a breakthrough that may now permit a wide variety of nonperturbative QCD calculations including, for example, high-precision B and D meson decay constants, mixing amplitudes, and semi-leptonic form factors—all quantities of great importance in current experimental work on heavy-quark physics. The breakthrough comes from a new discretization for light quarks: Symanzik-improved staggered quarks [1, 2, 3, 4, 5, 6, 7, 8].

Quark vacuum polarization is by far the most expensive ingredient in a QCD simulation. It is particularly difficult to simulate with small quark masses, such as u and d masses. Consequently, most lattice QCD (LQCD) simulations in the past have either omitted quark vacuum polarization ("quenched QCD"), or they have included effects for only u and d quarks, with masses 10–20 times larger than the correct values. This results in uncon-

Lattice Quantum Chromodynamics Comes of Age

Quentum chromodynamics is the elegant but notortously intractable theory of the strong Interactions. Recent advances in numerical computer simulation are beginning to reveal, in Impressive detail, what the theory predicts.

Carleton DeTar and Steven Gottlish

he strongth of the electron-photon interaction is charadericed by the fine-error arms constant at \$\times 1237.086. Because a is small, quantum electrodynamics (QED), the theory of interrecting executions and photons, run be solved to very good approximation with the traditional technology of schell and super. By contrast, quantum decembed, number (QCD), the generally accepted theory of strongly interacting quarks and gluons, has proven to be comunaably resistant to that represent But in recent yours, wivances in computer technology and algorithms have erroght the ab initio, numerical simulation of QCD to a leve, of crealbility that will have a significant impact on ottentilic discovery.

Lattice QCD

with t

to formulation, QCD and QED are a rikingly similar. Both are gauge invariant quartum field theories. The key differcurs is that prisibers in QXD one neutral; so they con't interact directly with each other The gluon is the QCD analog of the photon; it composits the groung force between quarks. For quite unlike photons, gluono do carry color charge, the analog of electric charge. So gluons interact directly with each other as well as with punches (See the article by Frank) Wileself in Persons Tonov, August 2000, page 32.)

That accomingly innerent change has dramatic consequarters for phenomenology. It is the root of QCD's doubt. ing complexity. Rections, positions, and photons can be separated and isolated at macroscopic distances. Quarter antiquerks, and gluons cannot. This prohibition, called color confinement, assures that all the elementary partities (the hadrons) composed of onerwa seriographs, and 6.0000 come in precise other neutral combinations. Locally speaking, this means that they come either in quara-untiquer's pairs (the mesons) or in Lights of quarks (the boryons). Several resently discovered 'pentaquark' botyons appear to combine a quark triple; with a quark-actiquark pair (see page 19 of this (esuc.)

Why unity critic-resented combinations? In QCD, quarter can have three-orders. Consecretate by they are labeled red, blue, and green, but of correse they have nothing to do with optics. Antiquarks have the corresponding anticolors. Pripleto of quartes containing squal portions of the three

Confetor DeTar III a website of website at the observable or that in that Lake Life Steven Golffish is a professor of physical archaetes University in Stevensylve.

SOME Arthur at a circum scratteractic con-

colors are salso mentral.

Try to pry leave one of the three valence quarks in a proton. Believe going much further than the rathers of Lie person fadaral 1 fm or 101-11 cm), and'se done snough work to create a new quark-entrquark pair. Pairo pampily appear, choose new partners, and you find a meson in one hand

and a proton or neutron in the other. No isolated quarks! At distances an order of magnitude smaller than I for equivalently, at interaction energies or momentum transfers in the much GeV range, a, the energy-dependcat QCD analog of the fine-surrecture constant, is west-field weak. In that limited regime, perturbation theory works, and pentil-and-paper methods succeed. But the the larger distances and softer interactions, where confinement is the dominating process, a, is effectively large and

we must recent to computerized numerical airmitation. In 1971, Kouneth Wilson at Ormell University formulated a version of QCD in a discrete spacetime britise (see the left panel of Space I) and, with pencil and paper, used it to provide a placerists, but not regrous, organization for odla confinement. Wilson argues, that, on a coarse specialisms between the potential energy of superation of a quark and an antiquark must rise linearly with distance. 1879 at Breakhayer, National Laboratory, Michael Crouts, Laurente Jasobs, and Claudic Robbs demonstrated the Lualidity of dury meaningful numerical simulations with Wilson's formulation on a Control Bate, Casp 7000 computer.3 Shartly therwatter, Crouts obtained at merical results for the confinement potential that supported Wison's conclusions. That success launched a new law who of computational physics, called bitting gauge theory or lattice QCD.3 The right panel of figure 1 shows a modern latlice-QCD result for the quark-antiquark potential.

High-precision calculations

For two decardes after Courte's properting 1979 calculations. estimate this in short have and computing power beought stouts guins in precision and conditioney. But only in the past four years have powerful algorithmic and theoretical improvements innucial us into the age of high-perciation lo.Le: QCD—at lesse for some key harboric quantities.

By the standards of the strong interactions, "high precision" means I or 2%. The impact of this new precision asheads beyond the strong interactions. Determining key feeburse of the word interactions of andreas. In example, the Cabibbo-Kabayashi Mashawa (CKM) parameterrequires correcting measural week decay rates for extrang interaction efficies (see box 1). The uncertainties in our invokelys of such fundamental parameters limits the precision with which the standard model of the elementary particles can be tested and probed for new walms of

the most impurbud thousafted advance in recon-

February 2004 - Physics Today 45

Lattice window on strong force

A long-awaited breakthrough has been made in lattice quantum chromodynamics - a means of calculating the effect of the strong force between sub-atomic particles that could, ultimately, unveil new physics.

> articles called quarks utrons, that are held rce. The heavier varihe decay rates is conthe standard model. sitive to new physical 3h accurate meas ve been made, the nding effect of the quarks modifies the ection factors can be is of any physics that st, Davies et al. report calculating the effect promises the calcula-l(C.T.H.Davies et al.

odel describes all l their interactions hanging other parti-For example, in an protons by swapping er. This is the electro ed by the theory of nics (OED). In a uark, called 'up' and ed gluons, that this is . Its associated theory amics, or QCD. In the third force, the weak ple of the weak force heavy bottom quark gh the emission of a itself decays to an ıtrino; Fig. 1a).

s unanswered. For observable Universe ere is no evidence for have been created in ach other: if a small

quark. In the standard model of particle physics, the process occurs through the weak force, mediate by a W particle, and also produces an electron and an anti-neutrino. b, In the real world, however, there is no such thing as a free quark. Instead, a bottom quark exists in a bound state with other ${\it quarks} -- {\it such as in a B meson, bound by the exchange of gluons to an anti-quark. Gluons and quarks}$ pairs are constantly emitted then reabsorbed; only a fraction of this 'sea' of particles is shown here. , So the realistic picture of the decay of a bottom quark is complex. The B meson — a bottom quark and anti-quark pair — becomes a pion (an up quark and an anti-quark), but the route is obscured by the mass of gluons and quarks (of which, again, only a fraction are shown). Calculating the details of the process is fiendishly complicated. But new advances in lattice quantum chromodynamics mean that precise theoretical correction factors can be worked out, and the problem effectively reduced to the simple process shown in a.

how did that asymmetry arise?

If heavy particles that existed in the early Universe decayed preferentially into matter over antimatter, that could have created the matter excess. In the standard model, two types of quark, bottom and strange, do decay asymmetrically. But this effect alone is far too small to account for the asymmetry. However, there are many theories that predict the existence of other, massive particles that of the Big Bang, there could readily produce the asymmetry. And particles, influenced by the unknown. If

ould be no matter in the Universe today. So because of the connection between asyn metry and mass, these theories also address almost 10,000 times lighter than bottom

> Searching for evidence of these particles accelerators, reaching ever higher energies, could create these mysterious particles; or there is the precision approach of looking for subtle deviations in the properties of known

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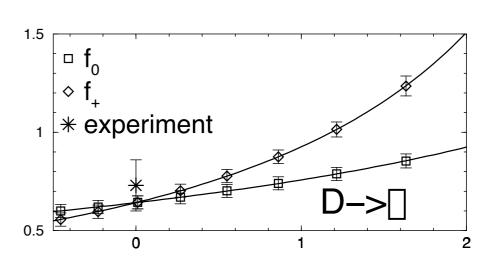
These are examples of some of the "golden quantities of lattice QCD: single stable meson processes. Other examples:

KK bar, BB bar, and BsBs bar mixing, $B \rightarrow \pi l \nu$, $B \rightarrow D l \nu$, $D \rightarrow \pi l \nu$, $D \rightarrow K l \nu$, $K \rightarrow \pi l \nu$.

Example of current work : $D \rightarrow \pi l \nu$.

Cleo-c will measure $f_D/D \rightarrow \pi l \nu$ and $f_{Ds}/D \rightarrow K l \nu$ to 2%. Interesting and rare CKM independent test of lattice heavy-light methods.

One-loop perturbative calcutions (in progress) will leave 8-10% perturbative uncertainties. Goal: make all other uncertainty significantly smaller than this.



M. Okamoto et al., at Lattice 2003, hep-lat/0309107.

Fermilab's lattice work is part of DoE's national effort to establish computational infrastructure for lattice QCD initiated under the SciDAC program.

US "Lattice QCD Executive Committee" (Sugar, chair, Brower, Christ, Creutz, Mackenzie, Negele, Rebbi, Sharpe, Watson) reports to DoE on plans and needs of US lattice QCD.

\$2M/year, three-year SciDAC grant will probably be extended through '05.

Two major components of national program:

Large, tightly coupled clusters (Fermilab/JLab):



Nonlocal communication through switch, well understood user environment.

QCDOC (Columbia/BNL):



Local, highly scalable communication.

Fermilab lattice cluster effort is led by Don Holmgren.

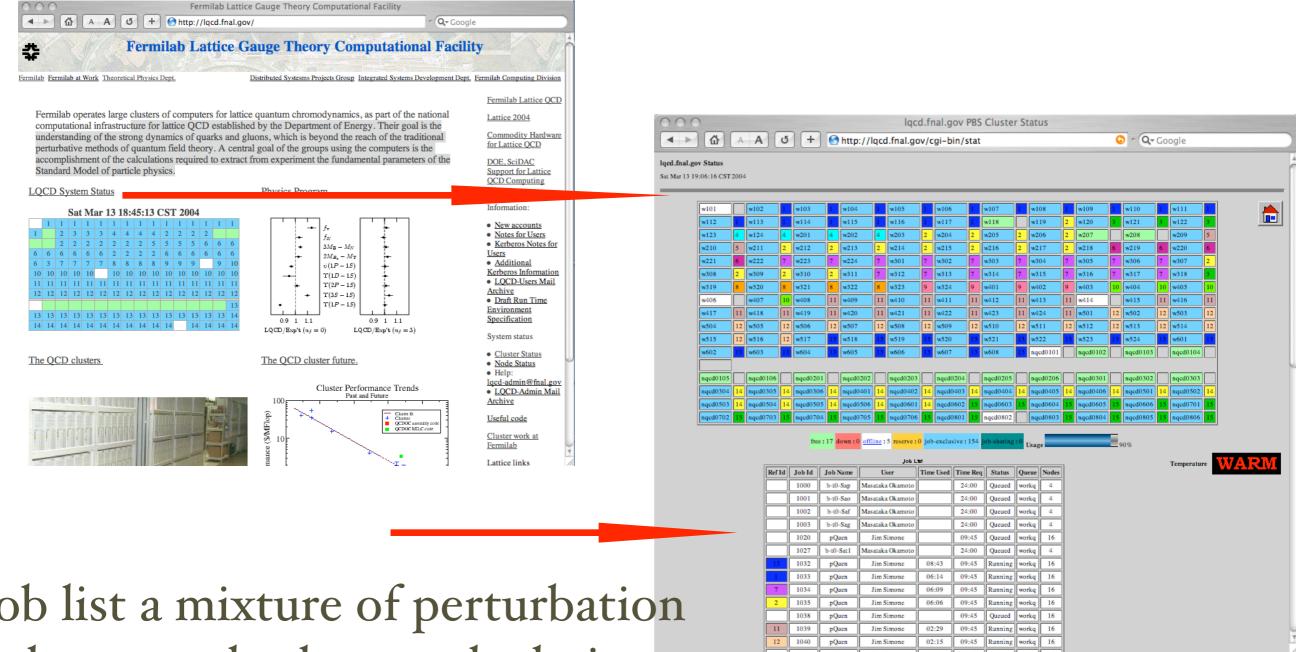
The clusters are currently housed in the New Muon Lab.



The 172 node Pentium 4 cluster. -100 GFlops.



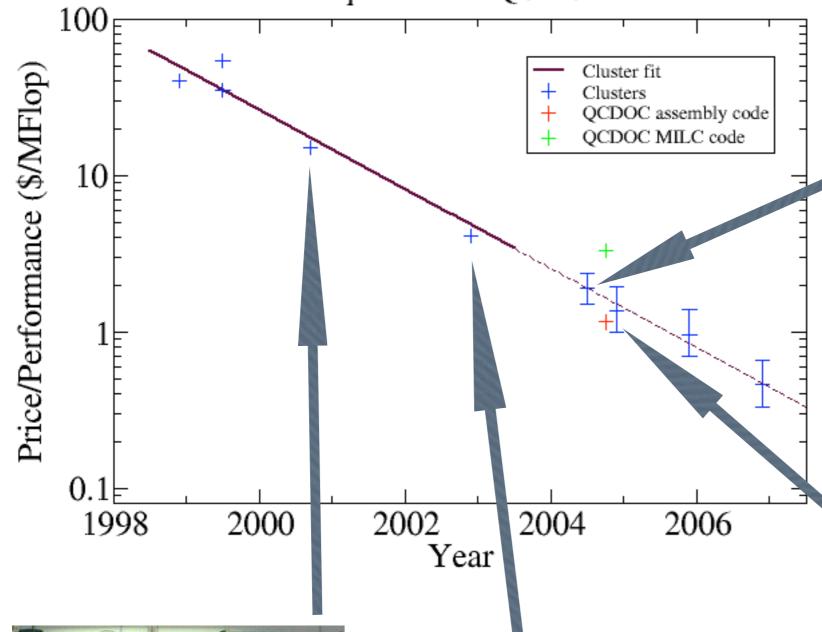
http://lqcd.fnal.gov



Job list a mixture of perturbation theory and valence calculation and analysis;

I node, 4 node, 16 node jobs, etc.

Cluster Performance Trends "Asqtad" Lattice QCD Code



2004:

128 P4 singles, reuse Myrinet switch. Incremental cost: \$1/MF.

256 node, P4 singles? Infiniband switch.

2005: 512 node, \$1M, 1 TF.

2006: 1024 node, \$1.5 M, 3 TF (or double).





At February, 2004 HEPAP meeting, Bob Sugar, in a well-received talk, reported the "absolute minimum support required for health of field".

Our answer: \$3M/year:

	2004	2005	2006	• • •
QCDOC	\$5M, 5 TF		\$ 0	
HEP Clusters	\$1 M, 1 TF		\$3 M, 6TF?	

DoE-HEP response: \$2M/year.

Discussions with Nuclear and ASCR are ensuing.